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Yasuda et al.

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(45) **Date of Patent: *Jan. 26, 2016**

(54) **COHERENT OPTICAL RECEIVER, APPARATUS AND METHOD FOR DETECTING INTERCHANNEL SKEW IN COHERENT OPTICAL RECEIVER**

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H04B 10/61 (2013.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04B 10/616*** (2013.01); ***H04B 10/6151*** (2013.01); *H04J 14/02* (2013.01); *H04J 14/06* (2013.01)

(58) **Field of Classification Search**
CPC H04B 10/697; H04B 10/6971; H04B 10/6972; H04B 10/616; H04B 10/6151; H04J 14/02; H04J 14/06
USPC 398/208, 209, 202, 158, 159
See application file for complete search history.

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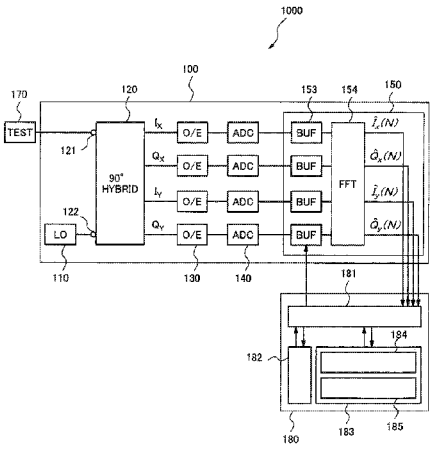
(57) **ABSTRACT**

In a coherent optical receiver, sufficient demodulation becomes impossible and consequently receiving performance deteriorates if an interchannel skew arises, therefore, a coherent optical receiver according to an exemplary aspect of the invention includes a local light source; a 90-degree hybrid circuit; an optoelectronic converter; an analog-to-digital converter; and a digital signal processing unit, wherein the 90-degree hybrid circuit makes multiplexed signal light interfere with local light from the local light source, and outputs a plurality of optical signals separated into a plurality of signal components; the optoelectronic converter detects the optical signals and outputs detected electrical signals; the analog-to-digital converter quantizes the detected electrical signals and outputs quantized signals; and the digital signal processing unit includes a skew compensation unit for compensating a difference in propagation delay between the plurality of signal components, and a demodulation unit for demodulating the quantized signals.

14 Claims, 12 Drawing Sheets



(51) **Int. Cl.**
H04J 14/02 (2006.01)
H04J 14/06 (2006.01)

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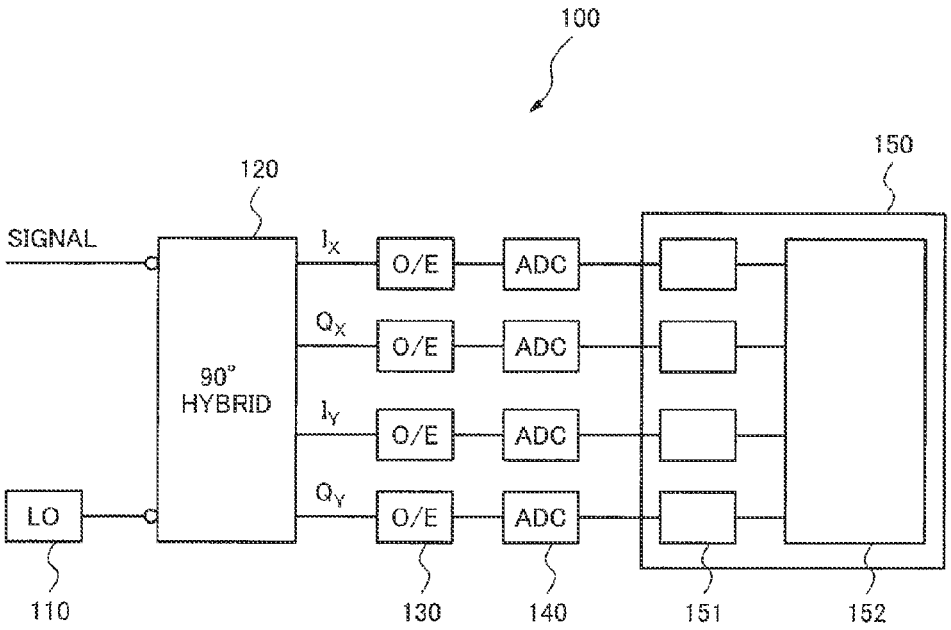
FIG. 1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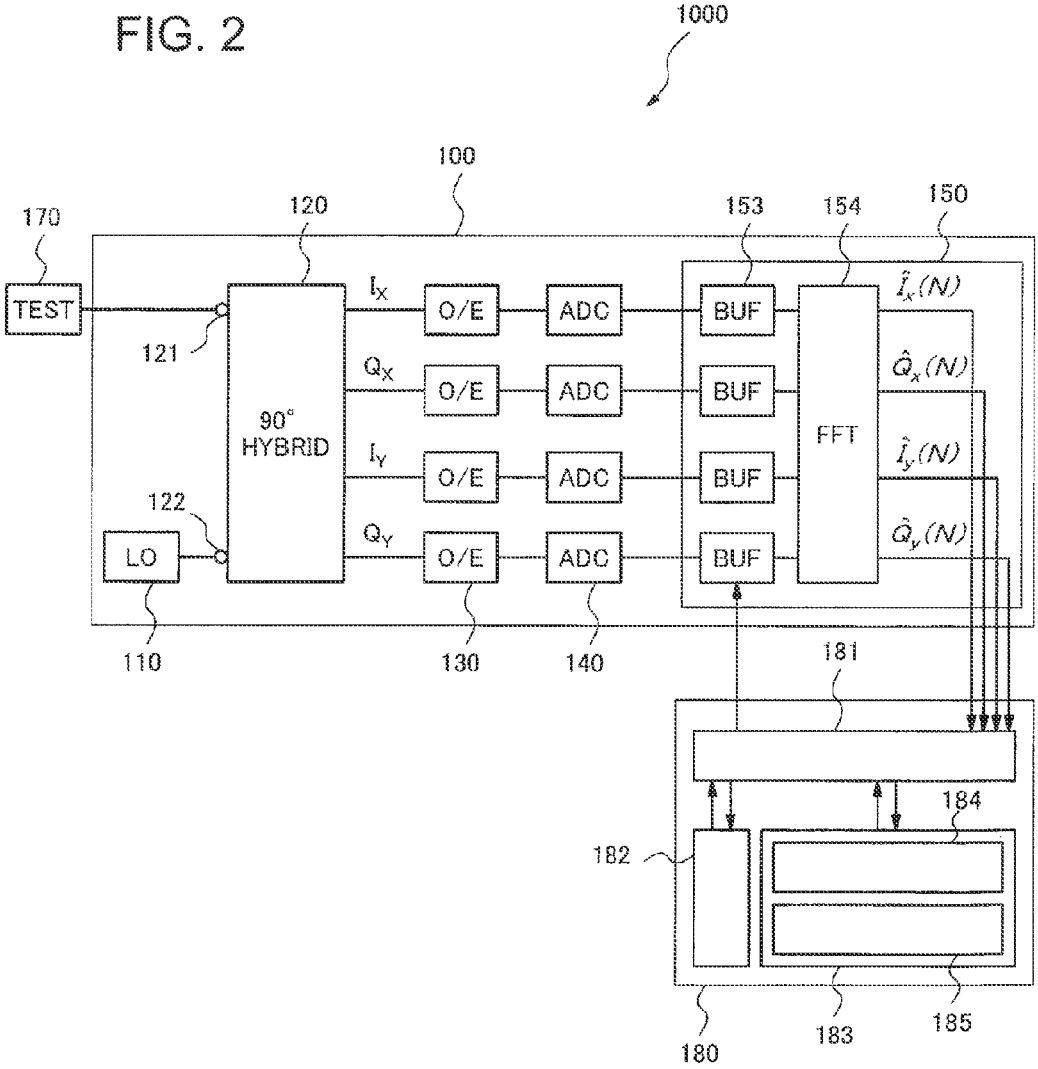
120
150
SIGNAL
LO
90°
HYBRID
I_X
Q_X
I_Y
Q_Y
O/E
O/E
O/E
O/E
ADC
ADC
ADC
ADC
110
130
140
151
152

FIG. 2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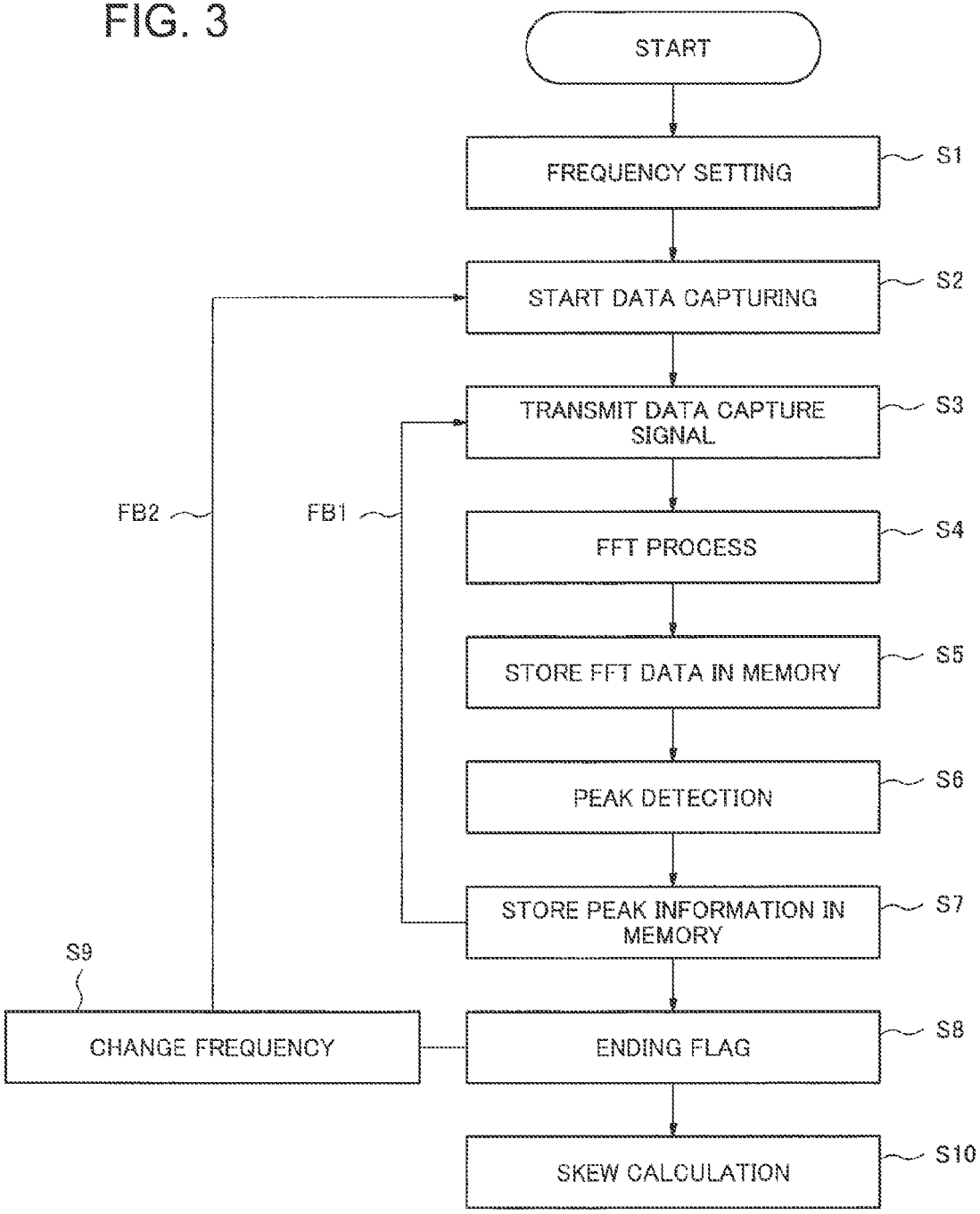
170
120
153
154
150
TEST
121
90°
HYBRID
I_X
Q_X
I_Y
Q_Y
O/E
O/E
O/E
O/E
ADC
ADC
ADC
ADC
BUF
BUF
BUF
BUF
FFT
$\hat{I}_x(N)$
$\hat{Q}_x(N)$
$\hat{I}_y(N)$
$\hat{Q}_y(N)$
122
LO
110
130
140
181
184
182
180
183
185

FIG. 3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FREQUENCY SETTING
S1
START DATA CAPTURING
S2
TRANSMIT DATA CAPTURE SIGNAL
S3
FB2
FB1
FFT PROCESS
S4
STORE FFT DATA IN MEMORY
S5
PEAK DETECTION
S6
STORE PEAK INFORMATION IN MEMORY
S7
S9
CHANGE FREQUENCY
ENDING FLAG
S8
SKEW CALCULATION
S10

FIG. 4

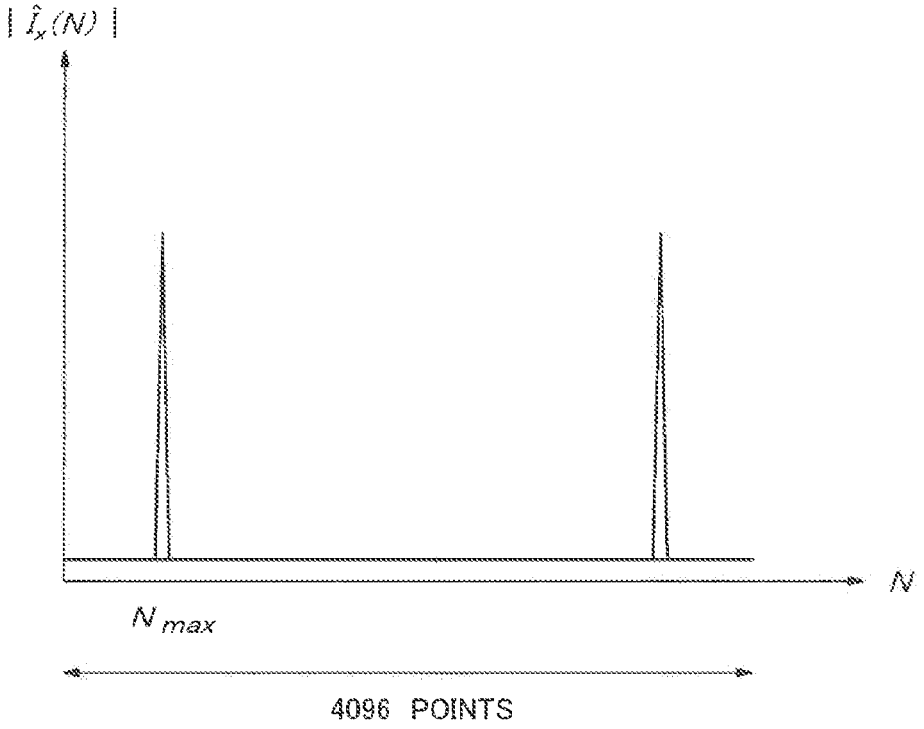

$|\hat{I}_x(N)|$
N
N_{max}
4096 POINTS

FIG. 5

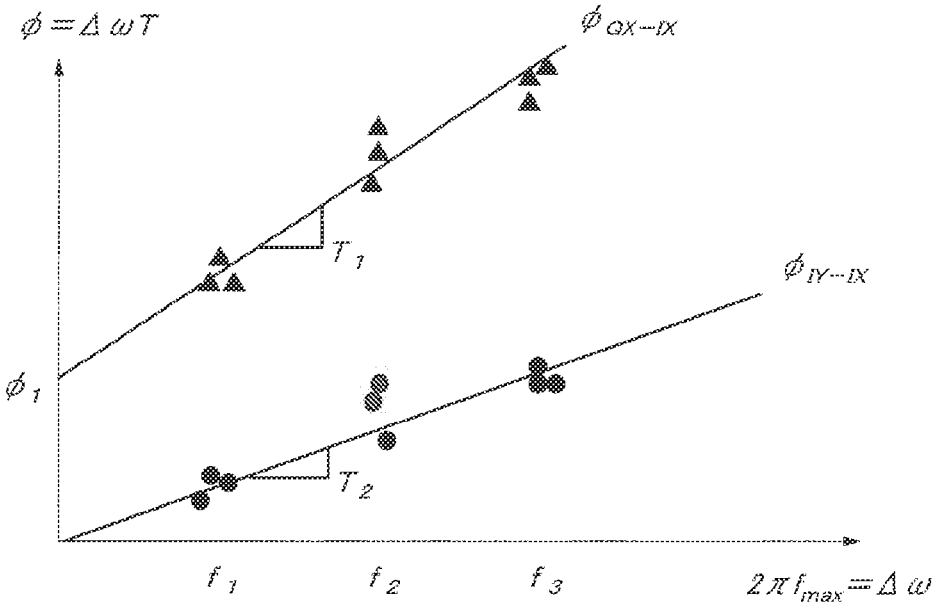

$\phi = \Delta\omega T$
ϕ_{QX-IX}
T_1
ϕ_{IY-IX}
ϕ_1
T_2
f_1
f_2
f_3
$2\pi f_{max} = \Delta\omega$

FIG. 6

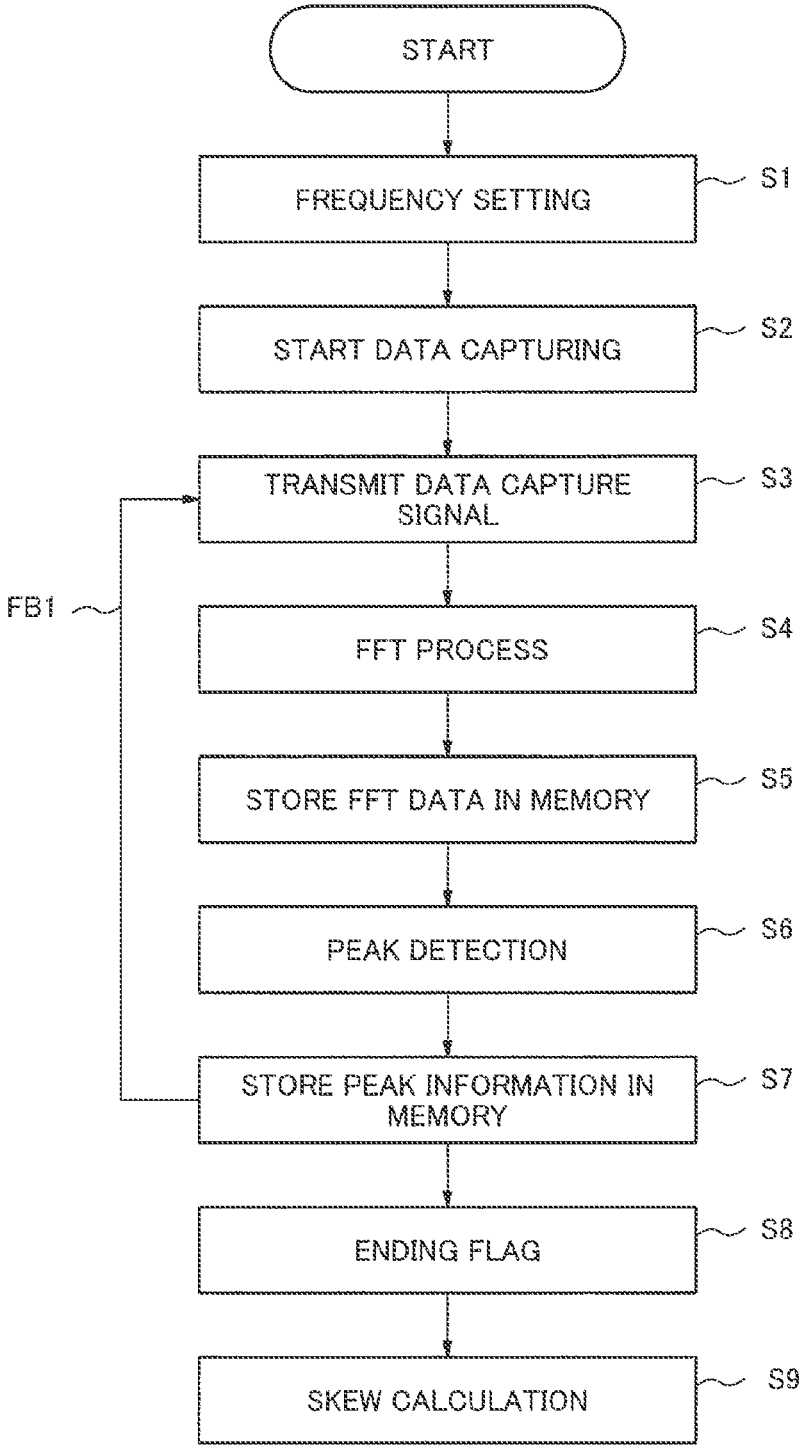

START
FREQUENCY SETTING
S1
START DATA CAPTURING
S2
TRANSMIT DATA CAPTURE SIGNAL
S3
FB1
FFT PROCESS
S4
STORE FFT DATA IN MEMORY
S5
PEAK DETECTION
S6
STORE PEAK INFORMATION IN MEMORY
S7
ENDING FLAG
S8
SKEW CALCULATION
S9

FIG. 7

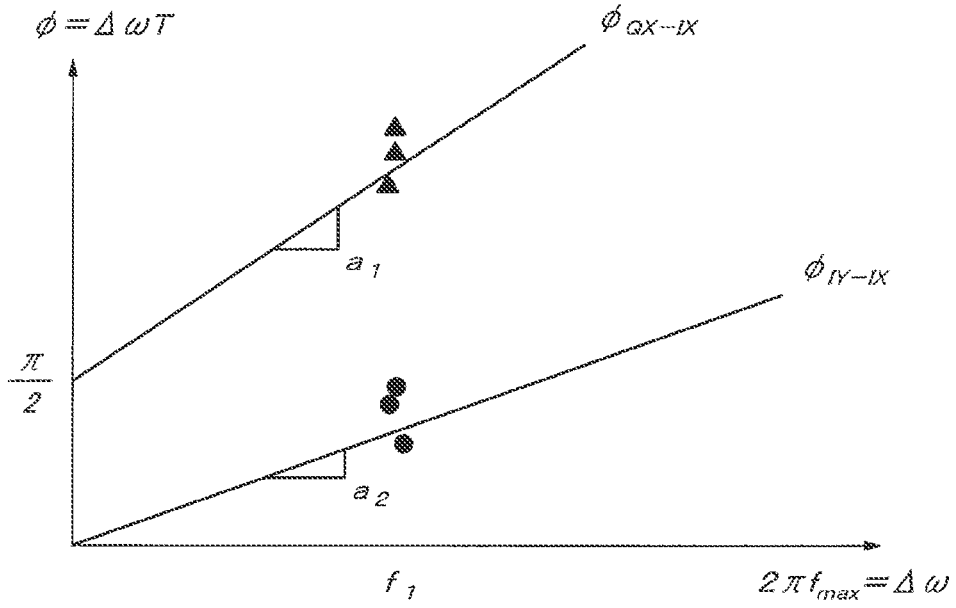
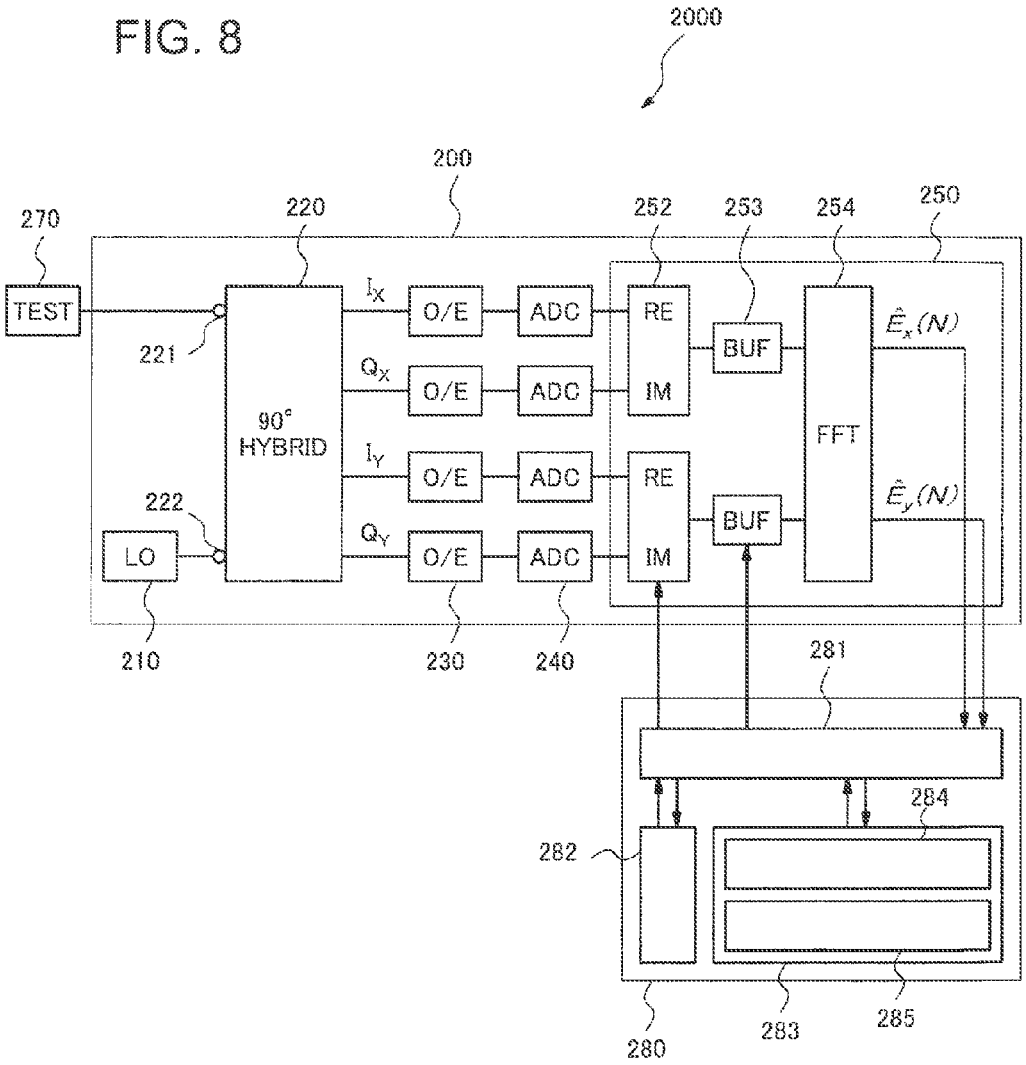

$\phi = \Delta\omega T$
ϕ_{QX-IX}
a_1
ϕ_{IY-IX}
$\frac{\pi}{2}$
a_2
f_1
$2\pi f_{max} = \Delta\omega$

FIG. 8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253
254
250
TEST
221
90°
HYBRID
I_X
Q_X
I_Y
Q_Y
O/E
O/E
O/E
O/E
ADC
ADC
ADC
ADC
RE
IM
RE
IM
BUF
BUF
FFT
$\hat{E}_x(N)$
$\hat{E}_y(N)$
222
LO
210
230
240
281
284
282
280
283
285

FIG. 9

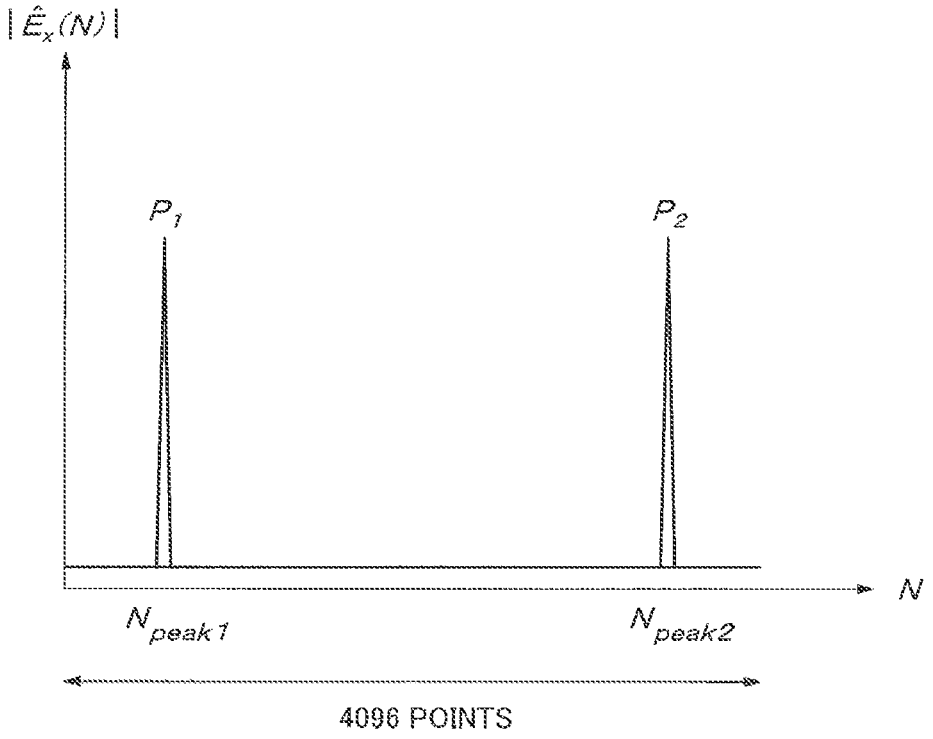


FIG. 10

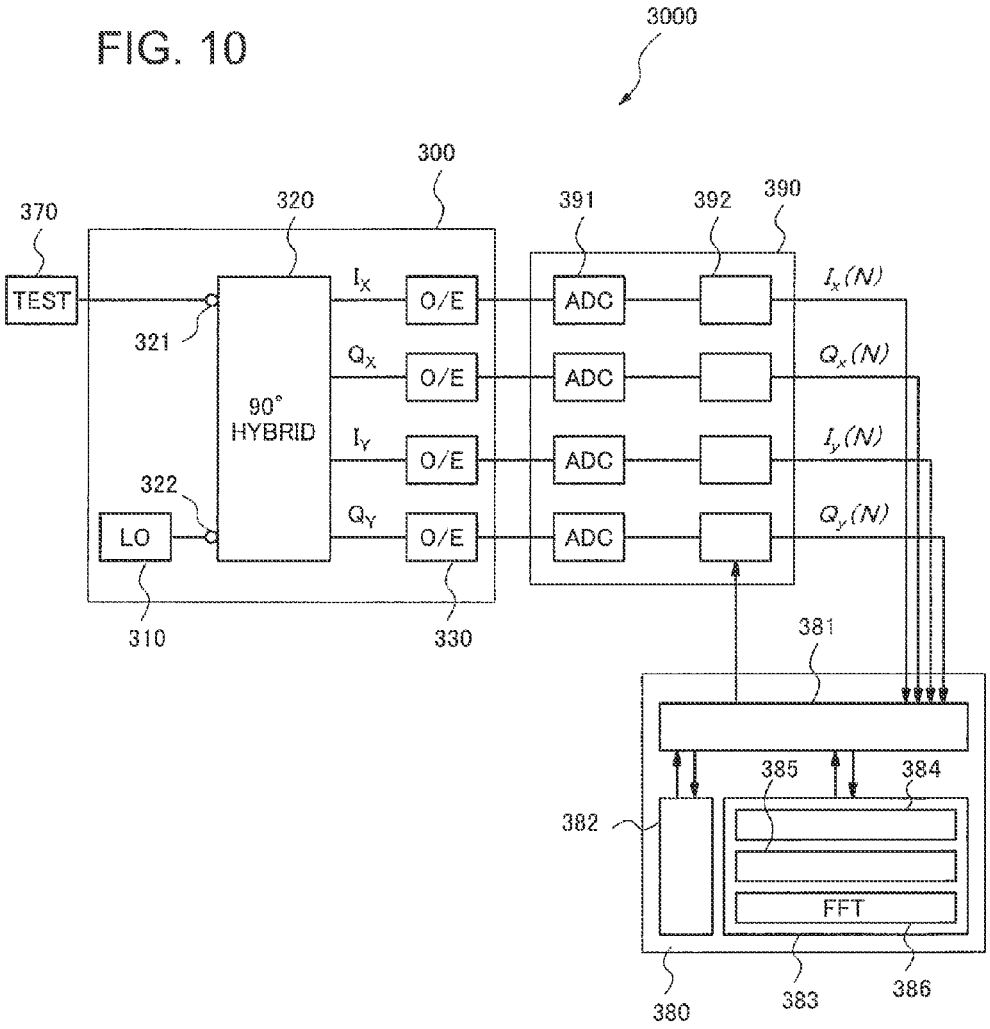

3000
300
370
320
391
392
390
TEST
321
90°
HYBRID
322
LO
310
I_X
Q_X
I_Y
Q_Y
O/E
O/E
O/E
O/E
330
ADC
ADC
ADC
ADC
$I_x(N)$
$Q_x(N)$
$I_y(N)$
$Q_y(N)$
381
385
384
382
FFT
380
383
386

FIG. 11

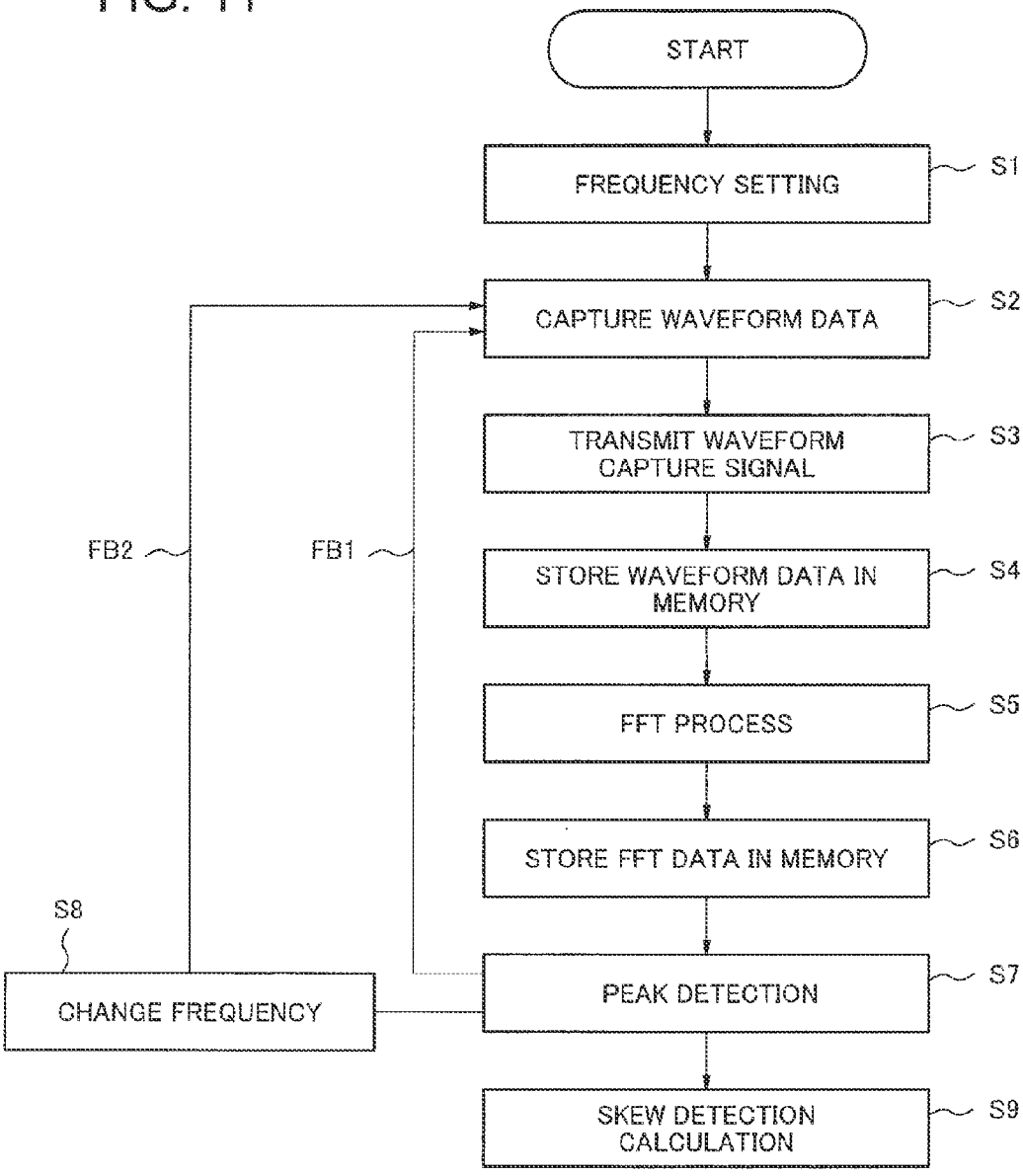

START
FREQUENCY SETTING
S1
CAPTURE WAVEFORM DATA
S2
TRANSMIT WAVEFORM CAPTURE SIGNAL
S3
STORE WAVEFORM DATA IN MEMORY
S4
FFT PROCESS
S5
STORE FFT DATA IN MEMORY
S6
PEAK DETECTION
S7
SKEW DETECTION CALCULATION
S9
CHANGE FREQUENCY
S8
FB1
FB2

FIG. 12

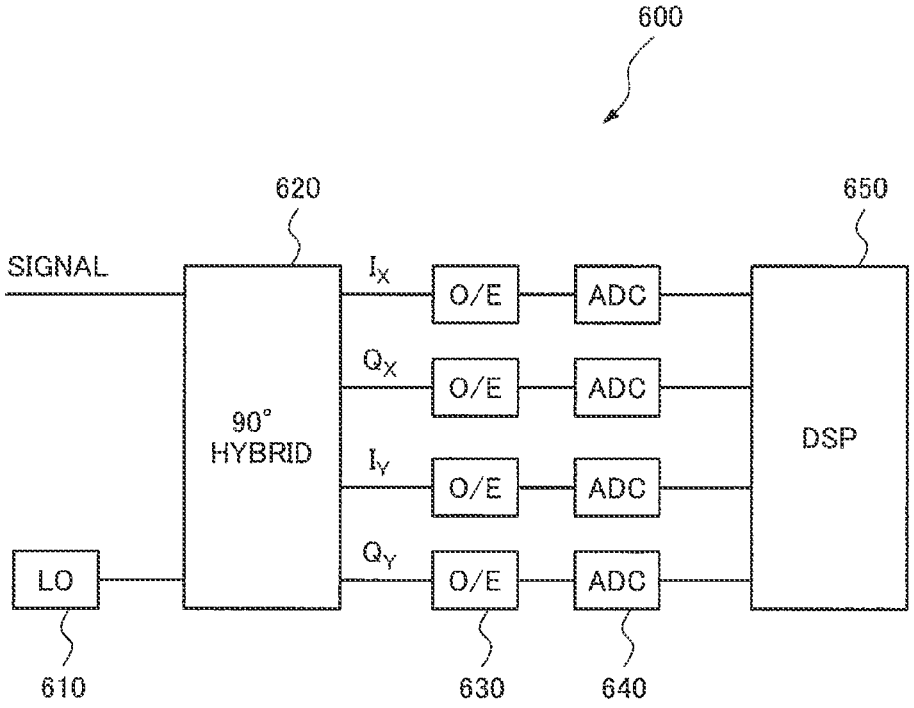
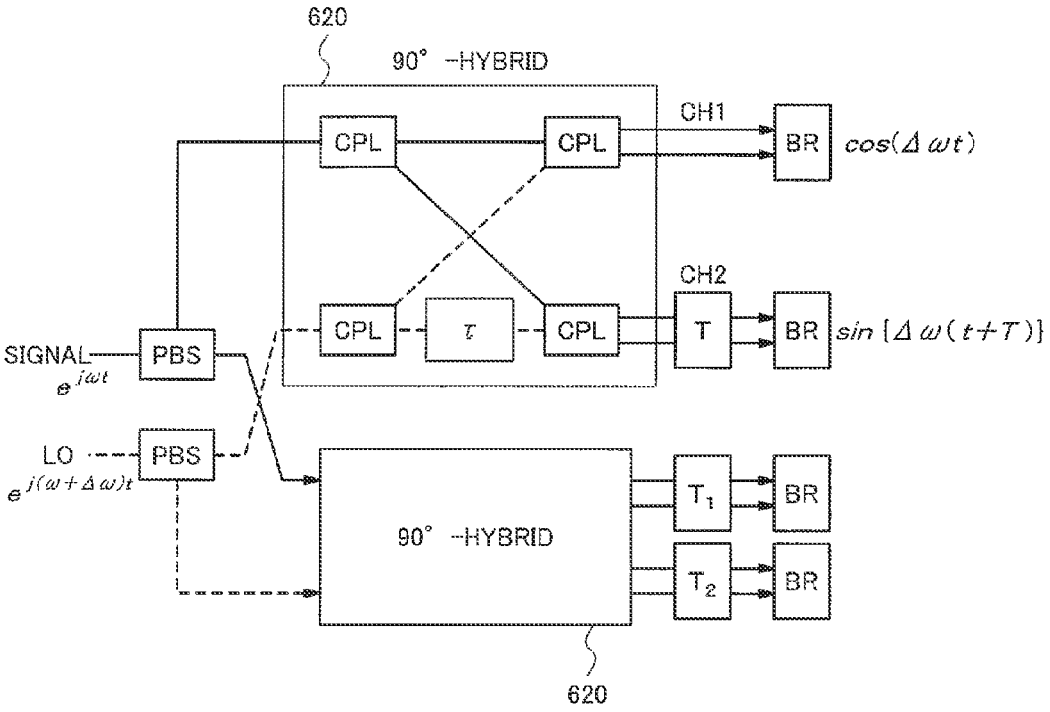

600
620
650
SIGNAL
I_X
O/E
ADC
Q_X
O/E
ADC
90°
HYBRID
I_Y
O/E
ADC
DSP
Q_Y
O/E
ADC
LO
610
630
640

FIG. 13


620
90° -HYBRID
CPL
CPL
CH1
BR
cos(Δωt)
CPL
τ
CPL
CH2
T
BR
sin [Δω(t+T)]
SIGNAL
e^jωt
PBS
LO
e^j(ω+Δω)t
PBS
90° -HYBRID
T1
BR
T2
BR
620

COHERENT OPTICAL RECEIVER, APPARATUS AND METHOD FOR DETECTING INTERCHANNEL SKEW IN COHERENT OPTICAL RECEIVER

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation application of U.S. application Ser. No. 13/696,516 filed Nov. 6, 2012, which claims priority from the National Stage of International Application No. PCT/JP2011/061601 filed May 13, 2011, claiming priority based on Japanese Patent Application No. 2010-116878 filed May 21, 2010, the contents of all of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

The present invention relates to coherent optical receivers, and apparatuses and methods for detecting interchannel skew in a coherent optical receiver, and, in particular, to a coherent optical receiver which receives polarization multiplexing optical signals by means of coherent detection and digital signal processing, and to an apparatus and a method for detecting interchannel skew in the coherent optical receiver.

BACKGROUND ART

The data capacity in the networks has been increasing year by year due to the wide spread of the Internet. In the trunk line connecting metropolitan areas, the optical transmission link whose transmission capacity per one channel is 10 Gb/s or 40 Gb/s has already been introduced. The On-Off-keying (OOK) is employed as a modulation scheme in 10 Gb/s transmission. Although the OOK scheme is also employed in 40 Gb/s transmission, it is unsuitable for long-haul transmission because the transmission characteristics are greatly influenced by the chromatic dispersion due to the narrow optical pulse width of 25 ps. Therefore, the multilevel modulation scheme using phase modulation and the polarization multiplexing scheme have been adopted, and the Dual Polarization Quadrature Phase Shift Keying (DP-QPSK) scheme is mainly employed for 100 Gb/s class transmission systems.

The optical signals modulated by DP-QPSK scheme in a transmitter are received and demodulated by a coherent optical receiver (refer to Non Patent Literature 1, for example). FIG. **12** shows an example of the configuration of a related coherent optical receiver. The related coherent optical receiver **600** has a local light source **610**, a 90-degree hybrid circuit (90° HYBRID) **620**, an optoelectronic converter (O/E) **630**, an analog-to-digital converter (ADC) **640**, and a digital signal processing unit (DSP) **650**.

Signal light and local light can be represented by the following formulae as a single polarization signal, respectively.

$$S(t)=\exp[j\omega t] \tag{1}$$

$$L(t)=\exp[j(\omega+\Delta\omega)t] \tag{2}$$

Here, $\Delta\omega$ represents a frequency offset between the signal light and the local light. The signal light and the local light are inputted into the 90-degree hybrid circuit (90° HYBRID) **620**, passing through an optical interference system, and converted into electric signals by the optoelectronic converters (O/E) **630**, each of which is composed of differentially configured photodiodes. At this time, the outputs represented by the following formulae (3) and (4) are obtained from an I_X port and a Q_X port, respectively.

$$I_X(t)=\cos(\Delta\omega t) \tag{3}$$

$$Q_X(t)=\sin(\Delta\omega t) \tag{4}$$

In the case of a polarization multiplexed signal, the signal light S (t) is expressed as $S(t)=E_X+E_Y$, the cosine components of the mixed signal of E_X+E_Y are outputted from I_X port and I_Y port, and the sine components of the mixed signal of E_X+E_Y are outputted from Q_X port and Q_Y port.

The signals outputted from each port are AD converted by the analog-to-digital converters (ADC) **640**, and then inputted into the digital signal processing unit (DSP) **650**. The digital signal processing unit (DSP) **650** demultiplexes inputted signals to E_X signal and E_Y signal by polarization demultiplexing processing, and demodulates the signals of E_X and E_Y into four levels by phase estimation processing.

In this way, the DP-QPSK signals can be demodulated by using the coherent optical receiver.

Non Patent Literature 1: M. G. Taylor, "Coherent Detection Method Using DSP for Demodulation of Signal and Subsequent Equalization of Propagation Impairments", IEEE Photonics Technology Letters, vol. 16, No. 2, February 2004, p. 674-676

DISCLOSURE OF INVENTION

Problem to be Solved by the Invention

The expressions of the signals in the above-described formulae (3) and (4) are true only if, in the coherent optical receiver **600**, all lengths of four signal lines from the outputs of the 90-degree hybrid circuit **620** to the inputs of the analog-to-digital converter **640** are equal. However, it is difficult to make precisely equal the length between those four channels, that is, the length of optical fiber cables from the output of the 90-degree hybrid circuit **620** to the inputs of the optoelectronic converters **630**, and the length of coaxial wires from the outputs of the optoelectronic converters **630** to the inputs of the analog-to-digital converters **640**.

Here, if the lengths of the lines are not equal between those four channels, there arises a delay in signal transmission, that is, a skew. The influence of the skew will be described referring to FIG. **13**. FIG. **13** is a block diagram showing the configuration of related 90-degree hybrid circuits **620** and their peripherals. In this figure, "PBS" represents a polarization beam splitter, "CPL" represents an optical coupler, "τ" represents a 90-degree phase difference unit, and "BR" represents a balanced photodetector as the optoelectronic converter (O/E) **630**, respectively.

If there exists a skew T in the channel **2** (CH**2**) against the channel **1** (CH**1**), the above-described formula (4) is changed into the following formula (5).

$$Q_X(t)=\sin(\Delta\omega(t+T)) \tag{5}$$

In the absence of the above-described skew T, the polarization demultiplexing and the phase estimation can be performed by the digital signal processing using the above-described formulae (3) and (4), and demodulation can be achieved perfectly. However, if there exists an interchannel skew, the output signal from the port Q_X expressed by the formula (4) changes into the output signal expressed by the formula (5), and the demodulation becomes imperfect even though the digital signal processing is performed, and thus sufficient performance can not be achieved. As described above, in a coherent optical receiver, there is a problem that sufficient demodulation becomes impossible and consequently receiving performance deteriorates if an interchannel skew arises.

The object of the present invention is to provide a coherent optical receiver and an apparatus and a method for detecting interchannel skew in the coherent optical receiver which

solve the problem mentioned above that in a coherent optical receiver, sufficient demodulation becomes impossible and consequently receiving performance deteriorates if an interchannel skew arises.

Means for Solving a Problem

A coherent optical receiver according to an exemplary aspect of the invention includes a local light source; a 90-degree hybrid circuit; an optoelectronic converter; an analog-to-digital converter; and a digital signal processing unit, wherein the 90-degree hybrid circuit makes multiplexed signal light interfere with local light from the local light source, and outputs a plurality of optical signals separated into a plurality of signal components; the optoelectronic converter detects the optical signals and outputs detected electrical signals; the analog-to-digital converter quantizes the detected electrical signals and outputs quantized signals; and the digital signal processing unit includes a skew compensation unit for compensating a difference in propagation delay between the plurality of signal components, and a demodulation unit for demodulating the quantized signals.

An apparatus for detecting interchannel skew in a coherent optical receiver according to an exemplary aspect of the invention includes a coherent optical receiver; a test light source; an analog-to-digital converter; an FFT operation unit; and a control block; wherein the coherent optical receiver includes a local light source, a 90-degree hybrid circuit, and an optoelectronic converter; the 90-degree hybrid circuit makes test light from the test light source interfere with local light from the local light source, and outputs a plurality of optical signals separated into a plurality of signal components; the optoelectronic converter detects the optical signals and outputs detected electrical signals; the analog-to-digital converter quantizes the detected electrical signals and outputs quantized signals; the FFT operation unit performs a fast Fourier transform process on the quantized signals; and the control block calculates a difference in propagation delay between the plurality of signal components from the results of the fast Fourier transform process.

A method for detecting interchannel skew in a coherent optical receiver according to an exemplary aspect of the invention includes the steps of: outputting a plurality of optical signals separated into a plurality of signal components by making test light from a test light source interfere with local light from a local light source; detecting the optical signals and outputting detected electrical signals; quantizing the detected electrical signals and outputting quantized signals; performing a fast Fourier transform process on the quantized signals; and calculating a difference in propagation delay between the plurality of signal components from the results of the fast Fourier transform process.

Effect of the Invention

According to the coherent optical receiver by the present invention, even if a skew arises between the channels, it becomes possible to achieve sufficient demodulation and thus to suppress deterioration of reception performance.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram showing the configuration of a coherent optical receiver in accordance with the first exemplary embodiment of the present invention.

FIG. **2** is a block diagram showing the configuration of an apparatus for detecting interchannel skew in the coherent optical receiver in accordance with the first exemplary embodiment of the present invention.

FIG. **3** is a flowchart illustrating a method for detecting interchannel skew in the coherent optical receiver in accordance with the first exemplary embodiment of the present invention.

FIG. **4** is a diagrammatic illustration where FFT data are plotted against point number, which are derived by an FFT operation unit in the coherent optical receiver in accordance with the first exemplary embodiment of the present invention.

FIG. **5** is a diagrammatic illustration plotting the relations between phase difference and angular frequency at Q_X port and I_Y port of the coherent optical receiver in accordance with the first exemplary embodiment of the present invention.

FIG. **6** is a flowchart illustrating another method for detecting interchannel skew in the coherent optical receiver in accordance with the first exemplary embodiment of the present invention.

FIG. **7** is a diagrammatic illustration plotting another set of the relations between phase difference and angular frequency at Q_X port and I_Y port of the coherent optical receiver in accordance with the first exemplary embodiment of the present invention.

FIG. **8** is a block diagram showing the configuration of an apparatus for detecting interchannel skew in the coherent optical receiver in accordance with the second exemplary embodiment of the present invention.

FIG. **9** is a diagrammatic illustration where FFT data are plotted against point number, which are derived by an FFT operation unit in the coherent optical receiver in accordance with the second exemplary embodiment of the present invention.

FIG. **10** is a block diagram showing the configuration of an apparatus for detecting interchannel skew in the coherent optical receiver in accordance with the third exemplary embodiment of the present invention.

FIG. **11** is a flowchart illustrating a method for detecting interchannel skew in the coherent optical receiver in accordance with the third exemplary embodiment of the present invention.

FIG. **12** is a block diagram showing the configuration of a related coherent optical receiver.

FIG. **13** is a block diagram showing the configuration of related 90-degree hybrid circuits and their peripherals.

DESCRIPTION OF EMBODIMENTS

The exemplary embodiments of the present invention will be described with reference to drawings below.

[The First Exemplary Embodiment]

FIG. **1** is a block diagram showing the configuration of a coherent optical receiver **100** in accordance with the first exemplary embodiment of the present invention. The coherent optical receiver **100** has a local light source **110**, a 90-degree hybrid circuit (90° HYBRID) **120**, optoelectronic converters (O/E) **130**, analog-to-digital converters (ADC) **140**, and a digital signal processing unit (DSP) **150**.

The 90-degree hybrid circuit (90° HYBRID) **120** makes multiplexed signal light (SIGNAL) interfere with the local light from the local light source **110**, and outputs a plurality of optical signals separated into respective signal components. In the present exemplary embodiment, the case will be described in which DP-QPSK modulation scheme is used. Accordingly, the 90-degree hybrid circuit (90° HYBRID) **120** outputs four-wave light signals including four-channel signal components respectively which are composed of in-phase

components (I_X, I_Y) and quadrature-phase components (Q_X, Q_Y) for each of two polarizations (X polarization and Y polarization).

The optoelectronic converter (O/E) **130** detects the respective light signals outputted from the 90-degree hybrid circuit **120**, and outputs the detected electrical signals. The analog-to-digital converter (ADC) **140** quantizes the detected electrical signals, and outputs the quantized signals.

The digital signal processing unit (DSP) **150** is provided with a skew compensation unit **151** which compensates the difference in propagation delay between a plurality of signal components (hereinafter, referred to as "skew"), and a demodulation unit **152**. The skew compensation unit **151** can be configured by using an FIR (Finite Impulse Response) filter and the like, for example; and in such a case, it holds filter coefficients which are determined on the basis of a skew value. The demodulation unit **152** separates the quantized signals into X polarization signals and Y polarization signals by the polarization demultiplexing process, and then demodulates each of the four-channel signal components by the phase estimation process.

Next, a method for detecting interchannel skew in the coherent optical receiver **100** will be described, referring to FIG. **2**. In the following, the case will be described in which the digital signal processing unit (DSP) **150** in the coherent optical receiver **100** is provided with a buffer unit (BUF) **153** and an FFT operation unit (FFT) **154**. Here, the FFT operation unit **154** performs a fast Fourier transform (referred to as "FFT", hereinafter) process on the quantized signals outputted by the analog-to-digital converter **140**. In FIG. **2**, illustrations of the skew compensation unit **151** and the demodulation unit **152** are omitted.

In the following, first, the case will be described in which there is a 90-degree error between I port and Q port in the 90-degree hybrid circuit. That is, although there is a delay corresponding to the signal cycle of 90 degree between I port and Q port in the 90-degree hybrid circuit, the phase difference does not necessarily correspond to 90 degree exactly due to the variability in the manufacturing process of the 90-degree hybrid circuit. Taking into account a delay $\Delta\tau$ due to the error in the 90-degree phase difference, the formula (5) described above is changed into the following formula (6).

$$Q_X(t)=\sin(\Delta\omega(t+T)+\Delta\tau) \tag{6}$$

When there exists this 90-degree error, the output signal from the port Q_X expressed by the formula (4) changes into the output signal expressed by the formula (6), and also in this case, the demodulation becomes insufficient even though digital signal processing is performed, and thus sufficient performance cannot be achieved.

As shown in FIG. **2**, a test light source **170** and a control block **180** are connected to the coherent optical receiver **100**, and thereby an apparatus for detecting interchannel skew in the coherent optical receiver **1000** is configured. The control block **180** includes a control unit **181**, a memory unit **182**, and an operational processing unit **183**. The operational processing unit **183** is provided with a peak detection unit **184** and a skew calculation unit **185**, and calculates a skew value from FFT processed results. Here, the peak detection unit **184** and the skew calculation unit **185** can be configured by specific signal processing circuits, and may also be configured by a central processing unit (CPU) and programs for enabling the CPU to execute a process.

The test light source (TEST) **170** is connected to a signal port **121** of the 90-degree hybrid circuit (90° HYBRID) **120**, and the local light source **110** is connected to a local port **122**. Light components outputted from the I_X, Q_X, I_Y, and Q_Y ports, which are output ports of the 90-degree hybrid circuit (90° HYBRID) **120**, are inputted into the optoelectronic converters (O/E) **130**, respectively.

In detecting interchannel skew in the coherent optical receiver **100**, first, a continuous wave (CW) light as a test light with a frequency f_S (its wavelength is equal to λ_S) is inputted from the test light source **170** into the signal port **121**. Here, a wavelength tunable light source can be used for the test light source **170**. On the other hand, a CW light as a local light of a frequency f_O (its wavelength is equal to λ_O) is inputted from the local light source **110** into the local port **122**. The test light of frequency fs and the local light of frequency f_O interfere in the 90-degree hybrid circuit **120**, and beat signals of a frequency $f_{IF}=|f_S-f_O|$ are outputted. Here, the beat signals outputted from the I_X, Q_X, I_Y, and Q_Y ports are represented by the following formulae form (7) to (10), respectively.

$$I_X=\cos(2\pi f_{IF}t+\phi_{IX}) \tag{7}$$

$$Q_X=\sin(2\pi f_{IF}t+\phi_{QX}) \tag{8}$$

$$I_Y=\cos(2\pi f_{IF}t+\phi_{IY}) \tag{9}$$

$$Q_Y=\sin(2\pi f_{IF}t+\phi_{QY}) \tag{10}$$

These beat signals are converted into electrical signals by the optoelectronic converters (O/E) **130**, quantized by the analog-to-digital converters (ADC) **140**, and then inputted into the digital signal processing unit (DSP) **150**, respectively. In the digital signal processing unit (DSP) **150**, the signals are divided into blocks with respect to each predetermined processing unit (4096 bits, for example) by buffer units **153**, and subjected to an FFT process in the FFT operation unit (FFT) **154**. As a result, each of matrices $\hat{I}_x(N)$, $\hat{Q}_x(N)$, $\hat{I}_y(N)$, and $\hat{Q}_y(N)$ is obtained as each output of the FFT operation unit **154**. Here, "N" represents a point number of FFT and it is equal to a value from 0 to 4095, for example.

Next, the method for detecting interchannel skew in the coherent optical receiver in accordance with the present exemplary embodiment will be described referring to the flowchart shown in FIG. **3**. First, the frequency of the test light source **170** is set at a frequency f_{S1} (its wavelength is equal to λ_{S1}) (step S**1**). Accordingly, a beat signal of a frequency $f_{IF}=|f_{S1}-f_O|$ is outputted from each output port of the 90-degree hybrid circuit (90° HYBRID) **120**.

Next, data capturing process is started (step S**2**). At that time, the control unit **181** in the control block **180** transmits a data capture signal to the digital signal processing unit (DSP) (step S**3**). The FFT operation unit **154** receives the data capture signal, triggered by the signal, it performs an FFT process on the data stored in the buffer unit (BUF) **153** at that time (step S**4**), and returns FFT data $\hat{I}_x(N)$, $\hat{Q}_x(N)$, $\hat{I}_y(N)$, and $\hat{Q}_y(N)$ to the control unit **181**. The control unit **181** stores the acquired FFT data in the memory unit **182** (step S**5**).

By an instruction from the control unit **181**, the peak detection unit **184** in the operational processing unit **183** extracts the data $\hat{I}_x(N_{max})$ having the maximum magnitude from 4096 points of the FFT data $\hat{I}_x(N)$. The frequency (peak frequency) f_{max} and the phase (peak phase) ϕ_{max} at that point are derived by calculation (step **6**). In FIG. **4**, a diagrammatic illustration is shown where $\hat{I}_x(N)$ are plotted against point number N. Here, since the FFT data $\hat{I}_x(N)$ are composed of complex numbers, the vertical axis of the figure represents the magnitude of $\hat{I}_x(N)$, $|\hat{I}_x(N)|$, and the horizontal axis represents the point number N in the FFT data. As shown in FIG. **4**, if $|\hat{I}_x(N)|$ has a peak value at the point number N_{max}, the peak detection unit **184** detects the $\hat{I}_x(N_{max})$. Here, f_T representing a sampling frequency in the analog-to-digital converters

(ADC) **140**, a frequency interval of the FFT process is equal to $f_T/4096$. Therefore, the peak frequency f_{max} at the peak of $\hat{I}_x(N)$ is equal to N_{max} f_T f/4096. And then, peak phase information $\phi_{max}=\angle(\hat{I}_x(N_{max}))$ is calculated by using the FFT data $\hat{I}_x(N_{max})$ at the peak frequency f_{max}.

In this way, the peak detection unit **184** derives the peak frequency f_{max} and the peak phase ϕ_{max} at the peak of the magnitude of the FFT data $\hat{I}_x(N)$, and the control unit **181** stores them in the memory unit **182** as a frequency $f_{IX(1,1)}$ and a phase $\phi_{IX(1,1)}$ (step S**7**). At that time, the other data of the FFT data $\hat{I}_x(N)$ can be eliminated.

In order to reduce the influence of a measurement error, the processes from step **3** to step **7** are repeated n times, and frequencies $f_{IX(1,n)}$ and phases $\phi_{IX(1,n)}$ are stored in the memory unit **182**, respectively (feedback loop FB**1**). When the n-th loop has been completed, an ending flag is set (step **8**).

Next, after changing the frequency of the test light source **170** into a frequency f_{S2} (step S**9**), the processes from step **2** to step **7** are repeated again, and then frequencies $f_{IX(2,n)}$ and phases $\phi_{IX(2,n)}$ are stored in the memory unit **182** (step S**7**). When detecting the ending flag (step S**8**), the frequency of the test light source **170** is further swept (step S**9**), and then the processes from step **2** to step **8** are repeated again (feedback loop FB**2**). By repeating the feedback loop FB**2** m times, frequencies $f_{IX(m,n)}$ and phases $\phi_{IX(m,n)}$ are stored in the memory unit **182**, respectively. By performing similar processes for $\hat{Q}_x(N)$, $\hat{I}_y(N)$, and $\hat{Q}_y(N)$, frequencies $f_{QX(m,n)}$, $f_{IY(m,n)}$, and $f_{QU(m,n)}$, and phases $\phi_{QX(m,n)}$, $\phi_{IY(m,n)}$, and $\phi_{QY(m,n)}$ are stored in the memory unit **182**, respectively.

When the above-mentioned processes have been completed, by an instruction from the control unit **181**, the skew calculation unit **185** in the operational processing unit **183** calculates skews (step **10**). For example, using the I_X port as a reference, a skew in the I_X port becomes zero, and a skew in each of the ports Q_X, I_Y, and Q_Y is represented by phase lead or phase lag against the I_X port. Specifically, first, the phase differences in the respective ports are obtained for a measurement cycle number n and a measurement frequency m by calculating the following quantities, respectively.

$$\phi_{IX(m,n)}=0$$

$$\phi_{QX(m,n)}-\phi_{IX(m,n)}$$

$$\phi_{IY(m,n)}-\phi_{IX(m,n)}$$

$$\phi_{QY(m,n)}-\phi_{IX(m,n)}$$

FIG. **5** shows a diagrammatic illustration plotting the relations between each phase difference of $\phi_{QX\text{-}IX}$ and $\phi_{IY\text{-}IX}$ in the Q_X port and I_Y port using the I_X port as a reference and the angular frequency $2\pi f_{max}$. By using this figure, approximation formulae represented by linear functions are derived for the Q_X port and I_Y port respectively, as follows.

$$\phi_{QX\text{-}IX}=T_1(2\pi f)+\phi_1$$

$$\phi_{IY\text{-}IX}=T_2(2\pi f)+\phi_2$$

An approximation formula is similarly derived for the Q_Y port as follows.

$$\phi_{QY\text{-}IX}=T_3(2\pi f)+\phi_3$$

Each gradient of T_1, T_2, and T_3 obtained here represents a skew against the I_X port. Here, the accuracy in the skew detection is obtained by the relation between the point number N of the FFT process and f_{IF}. For example, since a period is equal to 1 ns (=1000 ps) with f_{IF} being equal to 1 GHz, the accuracy of the skew detection becomes equal to 0.24 ps (=1000/4096) when N is equal to 4096. That is, it is found that the detection accuracy deteriorates with f_{IF} decreasing.

On the other hand, a phase difference in the Q_Y port against the I_Y port is represented as follows.

$$\phi_{QY(m,n)}-\phi_{IY(m,n)}$$

Here, the relation to the angular frequency $2\pi f_{max}$ is approximately represented by the following linear function, as is the case mentioned above.

$$\phi_{QY\text{-}IY}=T_4(2\pi f)+\phi_4$$

Since each of the phase differences $\phi_{QX\text{-}IX}$ and $\phi_{QY\text{-}IY}$ is equal to $\pi/2$ without frequency offset, each of ϕ_1 and ϕ_4 should become $\pi/2$. Therefore, the 90-degree error between the I_X port and the Q_X port, and that between the I_Y port and the Q_Y port become $\phi_1-\pi/2$ and $\phi_4-\pi/2$, respectively. Accordingly, by deriving ϕ_1 and ϕ_4 from the y-intercepts of the linear functions shown in FIG. **5**, the 90-degree errors in the I_Y port and the Q_Y port are obtained.

As mentioned above, according to the apparatus and the method for detecting interchannel skew in the coherent optical receiver of this exemplary embodiment, it becomes possible to calculate skews between the output ports and the 90-degree errors between the I port and the Q port. That is to say, it is possible to input test light into the signal port of the 90-degree hybrid circuit, observe beat signals between the test light and the local light by means of analog-to-digital converters, and calculate the skews and the 90-degree errors by using the phase information obtained by performing an FFT operation.

Furthermore, according to the coherent optical receiver **100** of the present exemplary embodiment, by compensating the skew values obtained above in the skew compensation unit **151** of the digital signal processing unit **150**, it becomes possible to demodulate sufficiently even though there arises a skew between the channels, and suppress the degradation of receiving performance.

In the above-mentioned exemplary embodiment, the 90-degree error between I port and Q port is calculated by obtaining the difference in peak phase between the channels at each of the frequencies with sweeping the frequency of the test light source as shown by the feedback loop FB**2** in FIG. **3**. However, if the 90-degree error can be neglected, it is possible to detect an inter-channel skew more simply.

FIG. **6** shows a flowchart of the method for detecting interchannel skew for this case. First, a frequency of the test light source **170** is set at a frequency f_{S1} (its wavelength is equal to λ_{S1}) (step S**1**). Accordingly, the beat signal of the frequency $f_{IF}=|f_{S1}-f_O|$ is outputted from each output port of the 90-degree hybrid circuit (90° HYBRID) **120**.

Next, data capturing process is started (step S**2**). At that time, the control unit **181** in the control block **180** transmits a data capture signal to the digital signal processing unit (DSP) **150** (step S**3**). The FFT operation unit **154** receives the data capture signal, triggered by the signal, it performs an FFT process on the data stored in the buffer units (BUF) **153** at that time (step S**4**), and returns FFT data $\hat{I}_x(N)$, $\hat{Q}_x(N)$, $\hat{I}_y(N)$, and $\hat{Q}_y(N)$ to the control unit **181**. The control unit **181** stores the acquired FFT data in the memory unit **182** (step S**5**).

By an instruction from the control unit **181**, the peak detection unit **184** in the operational processing unit **183** extracts the data $\hat{I}_x(N_{max})$ having the maximum magnitude from 4096 points of the FFT data $\hat{I}_x(N)$. The frequency (peak frequency) f_{max} and the phase (peak phase) ϕ_{max} at that point are derived by calculation (step S**6**). The control unit **181** stores this peak frequency and this peak phase in the memory unit **182** as a frequency $f_{IX(I)}$ and a phase $\phi_{IX(I)}$ (step S**7**).

In order to reduce the influence of a measurement error, the processes from step **3** to step **7** are repeated n times, and frequencies $f_{LX(n)}$ and phases $\phi_{LX(n)}$ are stored in the memory unit **182**, respectively (feedback loop FB**1**). When the n-th loop has been completed, an ending flag is set (step **8**).

When detecting the ending flag, by an instruction from the control unit **181**, the skew calculation unit **185** in the operational processing unit **183** calculates skews (step S**9**). For example, phase differences of the Q_X, I_Y, and Q_Y ports are obtained using the I_X port as a reference for number of measurements n respectively, as follows.

$$\phi_{LX(n)}=0$$

$$\phi_{QX(n)}-\phi_{LX(n)}$$

$$\phi_{IY(n)}-\phi_{LX(n)}$$

$$\phi_{QY(n)}-\phi_{LX(n)}$$

FIG. **7** shows a diagrammatic illustration plotting the relations between each phase difference of $\phi_{QX\text{-}LX}$ and $\phi_{IY\text{-}LX}$ in the Q_X port and I_Y port using the I_X port as a reference and the angular frequency $2\pi f_{max}$. Here, if a 90-degree error between the I port and the Q port can be neglected, approximation formulae represented by linear functions are derived for the Q_X port and I_Y port respectively, as follows.

$$\phi_{QX\text{-}LX}=a_1(2\pi f)+\pi/2$$

$$\phi_{IY\text{-}LX}=a_2(2\pi f)$$

An approximation formula can be similarly derived for the Q_Y port as follows.

$$\phi_{QY\text{-}LX}=a_3(2\pi f)$$

Each gradient of a_1, a_2, and a_3 obtained here represents a skew against the I_X port.

In this way, if a 90-degree error can be neglected, an interchannel skew can be detected more simply.

[The Second Exemplary Embodiment]

Next, the second exemplary embodiment of the present invention will be described. FIG. **8** is a block diagram showing the configuration of an apparatus for detecting interchannel skew in the coherent optical receiver **2000** in accordance with the second exemplary embodiment of the present invention. The apparatus for detecting interchannel skew in the coherent optical receiver **2000** includes a coherent optical receiver **200**, a test light source **270**, and a control block **280** connected to the coherent optical receiver **200**.

The coherent optical receiver **200** has a local light source **210**, a 90-degree hybrid circuit (90° HYBRID) **220**, optoelectronic converters (O/E) **230**, analog to digital converters (ADC) **240**, and a digital signal processing unit (DSP) **250**. The control block **280** includes a control unit **281**, a memory unit **282**, and an operational processing unit **283**, and the operational processing unit **283** is provided with a peak detection unit **284** and a skew calculation unit **285**.

In the coherent optical receiver **200** of the present exemplary embodiment, the configuration of the digital signal processing unit (DSP) **250** is different from that of the digital signal processing unit (DSP) **150** in accordance with the first exemplary embodiment. The digital signal processing unit (DSP) **250** is provided with a complex signal generator **252**, buffer units (BUF) **253**, and an FFT operation unit (FFT) **254**.

The test light source (TEST) **270** is connected to a signal port **221** of the 90-degree hybrid circuit (90° HYBRID) **220**, and the local light source **210** is connected to a local port **222**. Light components outputted from the I_X, Q_X, I_Y, and Q_Y ports, which are output ports of the 90-degree hybrid circuit (90° HYBRID) **220**, are inputted into the optoelectronic converters (O/E) **230**, respectively.

In detecting interchannel skew in the coherent optical receiver **200**, first, a continuous wave (CW) light as a test light of a frequency f_S (its wavelength is equal to λ_S) is inputted from the test light source **270** into the signal port **221**. Here, a wavelength tunable light source can be used for the test light source **270**. On the other hand, a CW light as a local light of a frequency f_O (its wavelength is equal to λ_O) is inputted from the local light source **210** into the local port **222**. The test light of frequency f_S and the local light of frequency f_O interfere in the 90-degree hybrid circuit **220**, and beat signals of a frequency $f_{IF}=|f_S-f_O|$ are outputted. Here, the beat signals outputted from the I_X, Q_X, I_Y, and Q_Y ports are represented by the above-mentioned formulae from (7) to (10) as is the case in the first exemplary embodiment.

These beat signals are converted into electrical signals by the optoelectronic converters (O/E) **230**, quantized by the analog-to-digital converters (ADC) **240**, and then inputted into the digital signal processing unit (DSP) **250**, respectively. In the digital signal processing unit (DSP) **250**, the signals from the I port and the Q port are synthesized, and then processed as complex signals. That is, the complex signal generator **252** receives I_x and Q_x, and outputs a complex signal of $E_x=I_x+jQ_x$. Similarly, it receives I_y and Q_y and outputs a complex signal of $E_y=I_y+jQ_y$.

These complex signals E_x and E_y are divided into blocks with respect to each predetermined processing unit (4096 bits, for example) by buffer units **253**, and subjected to an FFT process in the FFT operation unit (FFT) **254**. As a result, each of matrices $\hat{E}_x(N)$ and $\hat{E}_y(N)$ is obtained as each output of the FFT operation unit **254**. Here, "N" represents a point number of FFT and it is equal to a value from 0 to 4095, for example.

In this case, $\hat{E}_x(N)$ is represented by the following formulae.

$$\begin{aligned}\cos[\Delta\omega(t-T_1)]+j\sin[\Delta\omega(t-T_2)] &= \frac{1}{2}(e^{j\Delta\omega(t-T_1)}+e^{-j\Delta\omega(t-T_1)})+\\ &\quad \frac{1}{2}(e^{j\Delta\omega(t-T_2)}-e^{-j\Delta\omega(t-T_2)})\\ &= \frac{1}{2}\{e^{j\Delta\omega t}(e^{-j\Delta\omega T_1}+e^{-j\Delta\omega T_2})+\\ &\quad e^{-j\Delta\omega t}+(e^{j\Delta\omega T_1}-e^{j\Delta\omega T_2})\}\\ &= \frac{1}{2}\{e^{j\Delta\omega t}P_1+e^{-j\Delta\omega t}P_2\}\end{aligned}$$

where P_1, P_2, and $\Delta\omega$ are represented by the following formulae.

$$P_1=e^{-j\Delta\omega T_1}+e^{-j\Delta\omega T_2}$$

$$P_2=e^{j\Delta\omega T_1}-e^{j\Delta\omega T_2}$$

$$\Delta\omega=2\pi f_{IF}$$

Next, the method for detecting interchannel skew in the coherent optical receiver in accordance with the present exemplary embodiment will be described. The flow of its process is similar to that in the first exemplary embodiment, and therefore the following description will be given also referring to the flowchart shown in FIG. **3**. First, a frequency of the test light source **270** is set at a frequency f_{S1} (its wavelength is equal to λ_{S1}) (step S**1**). Accordingly, a beat signal of

a frequency $f_{IF}=|f_{S1}-f_O|$ is outputted from each output port of the 90-degree hybrid circuit (90° HYBRID) **220**.

Next, data capturing process is started (step S**2**). At that time, the control unit **281** in the control block **280** transmits a data capture signal to the digital signal processing unit (DSP) **250** (step S**3**). The FFT operation unit **254** receives the data capture signal, triggered by the signal, it performs an FFT process on the data stored in the buffer units (BUF) **253** at that time, and returns FFT data $\hat{E}_x(N)$ and $\hat{E}_y(N)$ to the control unit **281** (step S**4**). The control unit **281** stores the acquired FFT data in the memory unit **282** (step S**5**).

By an instruction from the control unit **281**, the peak detection unit **284** in the operational processing unit **283** extracts two peak values of $P_1=\hat{E}_x(N_{peak1})$ and $P_2=\hat{E}_x(N_{peak2})$ from 4096 points of the FFT data $\hat{E}_x(N)$. And then, the frequencies of $\pm 2\pi f_{IF}$ at that point are derived by calculation (step S**6**). In FIG. **9**, a diagrammatic illustration is shown where $\hat{E}_x(N)$ are plotted against point number N. Here, since the FFT data $\hat{E}_x(N)$ are composed of complex numbers, the vertical axis of the figure represents the magnitude of $\hat{E}_x(N)$, $\hat{E}_x(N)$, and the horizontal axis represents the point number N in the FFT data. As shown in FIG. **9**, if $\hat{E}_x(N)$ has peak values at the point numbers N_{peak1} and N_{peak2}, the peak detection unit **284** detects P_1 and P_2. Here, f_T representing a sampling frequency in the analog-to-digital converter (ADC) **240**, a frequency interval of the FFT process is equal to $f_T/4096$. Therefore, the peak frequencies at the peaks of $\hat{E}_x(N)$ are equal to $f_{peak1}=N_{peak1}\ f_T/4096$ and $f_{peak2}=-(4096\ N_{peak2})\ f_T/4096$, respectively.

Next, phase information of ϕ_{IX} and ϕ_{QX} are derived by calculation. First, the peak value P_1 is given by the following formula.

$$\begin{aligned} P_1 &= e^{-j\Delta\omega T_1} + e^{-j\Delta\omega T_2} \\ &= (\cos\Delta\omega T_1 + \cos\Delta\omega T_2) + j(-\sin\Delta\omega T_1 - \sin\Delta\omega T_2) \\ &= R_1 + jI_1 \end{aligned}$$

where R_1 and I_1 are represented by the following formulae.

$$R_1=\cos\Delta\omega T_1+\cos\Delta\omega T_2$$

$$I_1=\sin\Delta\omega T_1-\sin\Delta\omega T_2$$

Further, the peak value P_2 is given by the following formula.

$$\begin{aligned} P_2 &= e^{-j\Delta\omega T_1} - e^{-j\Delta\omega T_2} \\ &= (\cos\Delta\omega T_1 - \cos\Delta\omega T_2) + j(-\sin\Delta\omega T_1 + \sin\Delta\omega T_2) \\ &= R_2 + jI_2 \end{aligned}$$

where R_2 and I_2 are represented by the following formulae.

$$R_2=\cos\Delta\omega T_1-\cos\Delta\omega T_2$$

$$I_2=-\sin\Delta\omega T_1+\sin\Delta\omega T_2$$

By those formulae mentioned above, the following relational expressions are obtained.

$$R_1+R_2=2\cos\Delta\omega T_1$$

$$R_1-R_2=2\cos\Delta\omega T_2$$

$$I_1+I_2=-2\sin\Delta\omega T_1$$

$$I_1-I_2=-2\sin\Delta\omega T_2$$

By solving these relational expressions, the phase information of ϕ_{IX} and ϕ_{QX} are obtained respectively, as follows.

$$\begin{aligned} \phi_{IX} &= \Delta\omega T_1 \\ &= \tan^{-1}\left(\frac{-(I_1+I_2)}{R_1+R_2}\right) \end{aligned}$$

$$\begin{aligned} \phi_{QX} &= \Delta\omega T_2 \\ &= \tan^{-1}\left(\frac{-(I_1-I_2)}{R_1-R_2}\right) \end{aligned}$$

In this way, the peak detection unit **284** derives the frequency f_{peak1} and the peak phases ϕ_{IX} and ϕ_{QX} at the peak of the magnitude of the FFT data $\hat{E}_x(N)$, and the control unit **281** stores them in the memory unit **282** as a frequency $f_{X(1,1)}$, and phases $\phi_{IX(1,1)}$ and $\phi_{QX(1,1)}$, respectively (step S**7**). At that time, the other data of the FFT data $\hat{E}_x(N)$ can be eliminated.

In order to reduce the influence of a measurement error, the processes from step **3** to step **7** are repeated n times, and frequencies $f_{X(1,n)}$, and phases $\phi_{IX(1,n)}$ and $\phi_{QX(1,n)}$ are stored in the memory unit **282**, respectively (feedback loop FB**1**). When the n-th loop has been completed, an ending flag is set (step S**8**).

Next, after changing a frequency of the test light source **270** into a frequency f_{S2} (step S**9**), the processes from step **2** to step **8** are repeated again, and then frequencies $f_{X(2,n)}$ and phases $\phi_{IX(2,n)}$ and $\phi_{QX(2,n)}$ are stored in the memory unit **282** (step S**7**). When detecting an ending flag (step S**8**), a frequency of the test light source **270** is further swept (step S**9**), and then the processes from step **2** to step **8** are repeated again (feedback loop FB**2**). By repeating the feedback loop FB**2** m times, frequencies $f_{X(m,n)}$ and phases $\phi_{IX(m,n)}$ and $\phi_{QX(m,n)}$ are stored in the memory unit **282**, respectively. By performing similar processes for $\hat{E}_y(N)$, frequencies $f_{Y(m,n)}$ and phases $\phi_{IY(m,n)}$ and $\phi_{QY(m,n)}$ are stored in the memory unit **282**, respectively.

When the above-mentioned processes have been completed, by an instruction from the control unit **281**, the skew calculation unit **285** in the operational processing unit **283** calculates skews by a similar method to that in the first exemplary embodiment (step **10**).

As mentioned above, according to the apparatus and the method for detecting interchannel skew in the coherent optical receiver of this exemplary embodiment, it becomes possible to calculate skews between the output ports and 90-degree errors between I port and Q port. Moreover, by compensating the skew values obtained above in the skew compensation unit of the digital signal processing unit, with which the coherent optical receiver in accordance with the first exemplary embodiment is provided, it becomes possible to demodulate signals sufficiently even though there arises a skew between the channels, and suppress the degradation of receiving performance.

[The Third Exemplary Embodiment]

Next, the third exemplary embodiment of the present invention will be described. FIG. **10** is a block diagram showing the configuration of an apparatus for detecting interchannel skew in the coherent optical receiver **3000** in accordance with the third exemplary embodiment of the present invention. The apparatus for detecting interchannel skew in the coherent optical receiver **3000** has a coherent optical receiver **300**, a test light source **370**, a control block **380**, and a sampling oscilloscope **390** which are connected to the coherent optical receiver **300**

The coherent optical receiver **300** includes a local light source **310**, a 90-degree hybrid circuit (90° HYBRID) **320**,

and optoelectronic converters (O/E) **330**. The control block **380** includes a control unit **381**, a memory unit **382**, and an operational processing unit **383**, and the operational processing unit **383** is provided with a peak detection unit **384**, a skew calculation unit **385**, and an FFT operation unit (FFT) **386**.

In the present exemplary embodiment, the configuration is different from each of the first and the second exemplary embodiments in that it includes the sampling oscilloscope **390** instead of the digital signal processing unit (DSP) and the control block **380** is provided with the FFT operation unit (FFT) **386**. The sampling oscilloscope **390** is provided with four-channel analog-to-digital converters (ADC) **391** and memory units **392**.

The test light source (TEST) **370** is connected to a signal port **321** of the 90-degree hybrid circuit (90° HYBRID) **320**, and the local light source **310** is connected to a local port **322**. The beat signals outputted from the output ports of the 90-degree hybrid circuit (90° HYBRID) **320**, that is, I_X port, Qx port, I_Y port, and Q_Y port, are represented by the above-mentioned formulae from (7) to (10) as is the case in the first exemplary embodiment.

These beat signals are converted into electrical signals by the optoelectronic converters (O/E) **330**, quantized by the analog-to-digital converters (ADC) **391** in the sampling oscilloscope **390**, and then waveform data of $I_x(N)$, $Q_x(N)$, $I_y(N)$, and $Q_y(N)$ are stored in the memory unit **392**. Here, "N" represents the number of the data and takes the values from 0 to 4095, for example.

Next, referring to a flowchart shown in FIG. **11**, the method for detecting interchannel skew in the coherent optical receiver in accordance with the present exemplary embodiment will be described. First, the frequency of the test light source **370** is set at a frequency f_{S1} (its wavelength is equal to λ_{S1}) (step S**1**). Accordingly, a beat signal of a frequency $f_{IF}=|f_{S1}-f_O|$ is outputted from each output port of the 90-degree hybrid circuit (90° HYBRID) **320**.

Next, waveform data is captured in the sampling oscilloscope **390** (step S**2**). At that time, the control unit **381** in the control block **380** transmits a waveform capture signal to the sampling oscilloscope **390** (step S**3**). And then, the waveform data stored at that time in the memory unit **392** in the sampling oscilloscope **390** are stored in the memory unit **382** in the control block **380** (step S**4**).

The FFT operation unit (FFT) **386** in the control block **380** performs an FFT process on waveform data $I_x(N)$, $Q_x(N)$, $I_y(N)$, and $Q_y(N)$ stored in the memory unit **382** (step S**5**). And then, it returns the processed results of FFT data $\hat{I}_x(N)$, $\hat{Q}_x(N)$, $\hat{I}_y(N)$, and $\hat{Q}_y(N)$ to the control unit **381**. The control unit **381** stores the acquired FFT data in the memory unit **382** (step S**6**).

By an instruction from the control unit **381**, the peak detection unit **384** in the operational processing unit **383** extracts the data $\hat{I}_x(N_{max})$ having the maximum magnitude from 4096 points of the FFT data $\hat{I}_x(N)$. Then, the frequency f_{max} and the phase ϕ_{max} at that point are derived by calculation (step S**7**).

In order to reduce the influence of a measurement error, the processes from step **2** to step **7** are repeated n times, and frequencies $f_{IX(1,n)}$ and phases $\phi_{IX(1,n)}$ are stored in the memory unit **382**, respectively (feedback loop FB**1**). When the n-th loop has been completed, the frequency of the test light source **370** is changed into a frequency f_{S2} (step S**8**), the processes from step **2** to step **7** are repeated again, and then frequencies $f_{IX(2,n)}$ and phases $\phi_{IX(2,n)}$ are stored in the memory unit **382** (feedback loop FB**2**). By further sweeping the frequency of the test light source **370** and repeating the feedback loop FB**2** m times, frequencies $f_{IX(m,n)}$ and phases $\phi_{IX(m,n)}$ are stored in the memory unit **382**, respectively. By performing similar processes for $\hat{Q}_x(N)$, $\hat{I}_y(N)$, and $\hat{Q}_y(N)$, frequencies $f_{QX(m,n)}$, $f_{IY(m,n)}$, $f_{QY(m,n)}$, and phases $\phi_{QX(m,n)}$, $\phi_{IY(m,n)}$, and $\phi_{QY(m,n)}$ are stored in the memory unit **382**, respectively.

When the above-mentioned processes have been completed, by an instruction from the control unit **381**, the skew calculation unit **385** in the operational processing unit **383** calculates skews by a similar method to that in the first exemplary embodiment (step S**9**).

As mentioned above, according to the apparatus and the method for detecting interchannel skew in the coherent optical receiver of this exemplary embodiment, it becomes possible to calculate skews between the output ports and 90-degree errors between I port and Q port. Moreover, by compensating the skew values obtained above in the skew compensation unit of the digital signal processing unit, with which the coherent optical receiver in accordance with the first exemplary embodiment is provided, it becomes possible to demodulate signals sufficiently even though there arises a skew between the channels, and suppress the degradation of receiving performance.

In the above-mentioned exemplary embodiments, the coherent optical receiver is provided with the polarization diversity type of 90-degree hybrid circuit. However, the 90-degree hybrid circuit is not limited to that, a single polarization type of 90-degree hybrid circuit or its combination can be used.

In addition, although the test light source is connected to the signal port of the 90-degree hybrid circuit and sweeps frequencies in the above-mentioned exemplary embodiments, but not limited to this, by using a wavelength tunable laser as the local light source, the wavelength of the local light source can be swept with the wavelength of the test light source constant.

In the description above, the "I port" and the "Q port" mean signals outputted from the I port and the Q port, which are physical ports, respectively. However, the "I_X port", "Q_X port", "port I_Y port", and "Q_Y port" in the description about the formulae from (7) to (10) represent physical ports, respectively.

In the description about FIG. **12** and FIG. **13**, the phrase of "four channels" indicates four signal lines between the outputs of the 90-degree hybrid circuit **620** and the inputs of the analog-to-digital converter **640**. And "channel **1** (CH**1**)" indicates the I_X port, "channel **2** (CH**2**)" indicates the Q_X port, respectively.

The present invention is not limited to the above-mentioned exemplary embodiments and can be variously modified within the scope of the invention described in the claims. It goes without saying that these modifications are also included in the scope of the invention.

This application is based upon and claims the benefit of priority from Japanese patent application No. 2010-116878, filed on May 21, 2010, the disclosure of which is incorporated herein in its entirety by reference.

DESCRIPTION OF THE CODES

100, **200**, **300** coherent optical receiver
110, **210**, **310** local light source
120, **220**, **320** 90-degree hybrid circuit (90° HYBRID)
121, **221**, **321** signal port
122, **222**, **322** local port
130, **230**, **330** optoelectronic converter (O/E)
140, **240** analog-to-digital converter (ADC)
150, **250** digital signal processing unit (DSP)

151 skew compensation unit
152 demodulation unit
153, **253** buffer unit (BUF)
154, **254**, **386** FFT operation unit (FFT)
170, **270**, **370** test light source
180, **280**, **380** control block
181, **281**, **381** control unit
182, **282**, **382**, **392** memory unit
183, **283**, **383** operational processing unit
184, **284**, **384** peak detection unit
185, **285**, **385** skew calculation unit
252 complex signal generator
390 sampling oscilloscope
600 related coherent optical receiver
610 local light source
620 90-degree hybrid circuit (90° HYBRID)
630 optoelectronic converter (O/E)
640 analog-to-digital converter (ADC)
650 digital signal processing unit (DSP)
1000, **2000**, **3000** apparatus for detecting interchannel skew in coherent optical receiver

The invention claimed is:

1. A coherent optical receiver, comprising:
a local light source;
a 90-degree hybrid circuit;
an optoelectronic converter;
an analog-to-digital converter; and
a digital signal processing unit,
wherein the 90-degree hybrid circuit makes multiplexed signal light interfere with local light from the local light source, and outputs a plurality of optical signals separated into a plurality of signal components;
the optoelectronic converter detects the optical signals and outputs detected electrical signals;
the analog-to-digital converter quantizes the detected electrical signals and outputs quantized signals; and
the digital signal processing unit comprises an FFT operation unit for performing a fast Fourier transform process on the quantized signals, a skew compensation unit for compensating a difference in propagation delay between the plurality of signal components which is calculated from the results of the fast Fourier transform process, and a demodulation unit for demodulating the quantized signals.

2. The coherent optical receiver according to claim **1**, wherein the skew compensation unit compensates the difference in propagation delay which is calculated from a peak frequency and a peak phase at the maximum value in the results of the fast Fourier transform process.

3. An apparatus for detecting interchannel skew in a coherent optical receiver with the coherent optical receiver according to claim **1**, comprising:
a test light source; and
a control block;
wherein the 90-degree hybrid circuit makes test light from the test light source interfere with local light from the local light source, and outputs a plurality of optical signals separated into a plurality of signal components;
the control block calculates a difference in propagation delay between the plurality of signal components from the results of the fast Fourier transform process.

4. The apparatus for detecting interchannel skew in a coherent optical receiver according to claim **3**,
wherein the control block comprises a peak detection unit and a skew calculation unit;
the peak detection unit calculates a peak frequency and a peak phase at the maximum value in the results of the fast Fourier transform process for each of the plurality of signal components; and
the skew calculation unit calculates the difference in propagation delay from the peak frequency and the peak phase.

5. The apparatus for detecting interchannel skew in a coherent optical receiver according to claim **3**,
wherein the control block comprises a peak detection unit and a skew calculation unit;
the FFT operation unit performs a fast Fourier transform process on a signal resulting from synthesizing the quantized signals corresponding to the plurality of signal components;
the peak detection unit detects a plurality of peaks from the results of the fast Fourier transform process, and calculates a peak frequency and a peak phase at each of the plurality of peaks; and
the skew calculation unit calculates the difference in propagation delay from the peak frequency and the peak phase.

6. The apparatus for detecting interchannel skew in a coherent optical receiver according to claim **4**,
wherein the skew calculation unit sets the difference in propagation delay equal to a gradient of a linear function, by which a difference between the peak phase corresponding to each of the plurality of signal components is approximated against the peak frequency.

7. The apparatus for detecting interchannel skew in a coherent optical receiver according to claim **5**,
wherein the skew calculation unit sets the difference in propagation delay equal to a gradient of a linear function, by which a difference between the peak phase corresponding to each of the plurality of signal components is approximated against the peak frequency.

8. An apparatus for detecting interchannel skew in a coherent optical receiver with the coherent optical receiver according to claim **2**, comprising:
a test light source; and
a control block;
wherein the 90-degree hybrid circuit makes test light from the test light source interfere with local light from the local light source, and outputs a plurality of optical signals separated into a plurality of signal components;
the control block calculates a difference in propagation delay between the plurality of signal components from the results of the fast Fourier transform process.

9. The apparatus for detecting interchannel skew in a coherent optical receiver according to claim **8**,
wherein the control block comprises a peak detection unit and a skew calculation unit;
the peak detection unit calculates a peak frequency and a peak phase at the maximum value in the results of the fast Fourier transform process for each of the plurality of signal components; and
the skew calculation unit calculates the difference in propagation delay from the peak frequency and the peak phase.

10. The apparatus for detecting interchannel skew in a coherent optical receiver according to claim **8**,
wherein the control block comprises a peak detection unit and a skew calculation unit;
the FFT operation unit performs a fast Fourier transform process on a signal resulting from synthesizing the quantized signals corresponding to the plurality of signal components;

the peak detection unit detects a plurality of peaks from the results of the fast Fourier transform process, and calculates a peak frequency and a peak phase at each of the plurality of peaks; and

the skew calculation unit calculates the difference in propagation delay from the peak frequency and the peak phase.

11. The apparatus for detecting interchannel skew in a coherent optical receiver according to claim **9**,

wherein the skew calculation unit sets the difference in propagation delay equal to a gradient of a linear function, by which a difference between the peak phase corresponding to each of the plurality of signal components is approximated against the peak frequency.

12. The apparatus for detecting interchannel skew in a coherent optical receiver according to claim **10**,

wherein the skew calculation unit sets the difference in propagation delay equal to a gradient of a linear function, by which a difference between the peak phase corresponding to each of the plurality of signal components is approximated against the peak frequency.

13. A method for receiving coherent light, comprising the steps of

making multiplexed signal light interfere with local light from a local light source, and outputting a plurality of optical signals separated into a plurality of signal components;

detecting the optical signals and outputting detected electrical signals; quantizing the detected electrical signals and outputting quantized signals; performing a fast Fourier transform process on the quantized signals; and compensating a difference in propagation delay between the plurality of signal components which is calculated from the results of the fast Fourier transform process.

14. The method for receiving coherent light according to claim **13**, further comprising:

in the step of compensating the difference in propagation delay,

compensating the difference in propagation delay which is calculated from a peak frequency and a peak phase at the maximum value in the results of the fast Fourier transform process.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,246,599 B2
APPLICATION NO. : 14/078725
DATED : January 26, 2016
INVENTOR(S) : Wakako Yasuda, Junichi Abe and Kiyoshi Fukuchi

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title Page

(73) Assignee: Delete "NEC CORPORAITON," and insert --NEC CORPORATION,--

Specification

Column 7, Line 3: Delete "f_T f/4096." and insert --f_T/4096.--

Column 7, Line 29: Delete "$f_{QU\ (m,\ n)}$," and insert --$f_{QY\ (m,n)}$,--

Column 7, Line 65: Delete "f_{rF}." and insert --f_{IF}.--

Column 8, Line 67: Delete "$f_{IX(I)}$" and insert --$f_{IX(1)}$--

Column 8, Line 67: Delete "$\phi_{IX(I)}$" and insert --$\phi_{IX(1)}$--

Column 11, Line 20: Delete "$\hat{E}_x(N)$," and insert --$|\hat{E}_x(N)|$,--

Signed and Sealed this
First Day of November, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office